# Possibilities for a Diffraction-Limited Upgrade of a Soft X-Ray Light Source[1]

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## Introduction

Over the last decades, synchrotron radiation generated by storage rings has been the dominant source of high brightness photons in a spectrum spanning from infrared to hard X-rays for a multitude of scientific applications. During those years, accelerator and source development has seen several step changes denoted by three generations of ring-based synchrotron light sources. Since the advent of 3rd generation sources about 20 years ago, development has continued but until recently had been mostly evolutionary. In the meantime free electron lasers (FELs) have emerged as alternative sources of soft and hard X-rays, offering peak brightness many orders of magnitude higher than storage ring sources, with ultra-short photon pulses having nearly complete transverse coherence and an energy bandwidth that approaches the transform limit with seeding. Yet, in spite of these spectacular beam properties, a consensus has emerged that ring-based sources will continue to play a vital role in X-ray science into the future because they offer beam properties that are complementary to FEL sources. Storage rings provide photons beams with lower peak brightness but high average brightness and higher pulse repetition rates, on a large number of parallel beamlines with excellent stability and quick tunability [1,2]. Recent advances in accelerator physics and engineering have made it feasible to provide another step change in brightness over 3rd generation storage rings. The first rings applying some of those technologies are under construction now.

There are many scientific applications and experimental methods that can greatly benefit from much higher brightness and transverse coherence than present storage ring facilities can provide. Those include nanometer imaging applications, x-ray correlation spectroscopy, diffraction microscopy, holography, ptychography, and resonant inelastic soft x-ray scattering at high resolution [3,4,5]. Specifically for soft x-rays, which are not as penetrating as hard x-rays, but provide chemical contrast, the strongest science applications are seen in three areas:

- Three-dimensional imaging down to few nm resolution with chemical, electronic, or magnetic contrast.
- Q-resolved resonant inelastic x-ray scattering (q-RIXS) combined with dispersive spectroscopy.
- Correlation spectroscopy over various length (nm to mm) and time scales (ps to s).

An international workshop will be held in October 2014 at the Advanced Light Source (ALS) in Berkeley to further refine the science case for lower/intermediate energy facility upgrades now under consideration worldwide.

## Design Trade-offs

High brightness and transversely coherent radiation is generated if the electron beam emittance is near or smaller than the diffraction limit for X-ray energies of interest. Given that the diffraction-limited emittance for a photon wavelength $\lambda$ is $\lambda/4\pi$, electron emittance on the scale of about 50 pm-rad is needed for soft X-rays (2 keV), whereas an emittance smaller than 10 pm-rad is necessary for

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hard x-rays (>10 keV). Such emittances are obtained vertically in existing storage rings, but are far smaller than the >1000 pm-rad horizontal emittances existing rings deliver. Furthermore, current rings with larger horizontal emittances deliver "flat" beams that are not optimally matched into focusing optics. Ideally one would like to achieve diffraction-limited emittances in both planes. Over the last 5 years, a consensus has emerged that diffraction limited storage rings (DLSR) can provide diffraction-limited beams based on a modest extrapolation of present-day technology [2].

Most designs under consideration for diffraction limited light sources make use of multi-bend achromat lattices [1]. The first proposals for such lattices were made in the 1990s and recently construction has started on the first implementation of the concept at MAX-IV. The required magnet strengths to realize small equilibrium emittances are enabled by smaller vacuum chamber apertures and smaller magnet bores. Multi-bend achromat rings have been studied both as upgrades to existing facilities, as well as newly-built facilities. In general, upgrades can be more cost effective and reduce the time necessary to get a broad set of user beamlines into operation. However, minimizing the dark time for existing beamlines and adjusting the design to infrastructure boundary conditions can be challenging for upgrades.

Current proposals and projects around the world span a wide range of facility sizes, as well as photon and electron beam energies. While some of the design and technology challenges are similar across all rings, other design trade-offs are strongly affected by the choice of photon energy range for which the proposal is optimized. Some of the reasons for this are:

- Very different diffraction limited emittances for soft vs. hard x-rays
- Different electron beam energies that enable the use of optimized undulators for the photon energy range of choice
- Very strong energy scaling of intrabeam scattering (IBS)
- Photon beam heat load

In this article, we will focus on the possibilities of a diffraction limited soft x-ray upgrade. The specific example we will use for illustration below is a hypothetical future upgrade of the Advanced Light Source.

## Case Study for an Upgrade of a Soft X-ray Storage Ring

The 2-GeV Advanced Light Source (ALS) at Berkeley Lab has been updated many times and remains one of the brightest sources for soft x-rays worldwide. However, a multi-bend achromat upgrade, similar to what is considered for several facilities, would open the door for much larger future brightness improvements by reducing the horizontal emittance. Such an upgrade could reuse the existing tunnel, as well as much of the infrastructure and beamlines. In the following we discuss some of the design considerations.

With current state-of-the-art insertion device technology, the peak of the facility brightness envelope for 2 GeV electron beam energy lies well above 1 keV. Considering further insertion device developments already under way, specifically PrFeB cryogenic in-vacuum undulators as well as superconducting undulators, this will extend to almost 3 keV. Raising the electron beam energy above 2 GeV (while keeping the beam emittance the same) would not result in higher brightness in the soft x-ray range. In fact, generic scaling studies which we carried out for the 500 eV to 2 keV range showed that rings with beam energies larger than 2 GeV either have larger photon optics heat load for similar brightness, or substantially lower brightness for a similar heat load, assuming equal emittances and insertion device technology. So as long as diffraction-limited emittances for 2 keV photon energy can be achieved, which we will show below is true for a 2 GeV ring of 200 m circumference, such a ring would provide optimal soft x-ray brightness.

Choosing such relatively low electron beam energy has several other consequences. On the positive side, it allows much shorter focal lengths for quadrupoles (and stronger energy normalized sextupoles) for the same pole tip magnetic fields. This potentially allows the use of shorter magnets, and higher phase advance per sector resulting in smaller equilibrium emittances. While very high phase advances in high energy rings with 30-40 sectors could require unachievable sextupole strengths, a 2 GeV ring with only 12 sectors and the corresponding larger bending angle per dipole has larger dispersion functions keeping the necessary sextupole strengths feasible.

On the negative side, IBS, which tends to lead to an emittance increase at larger bunch charge, is a very rapid function of the beam energy and, therefore, is much more severe at 2 GeV compared to higher energy rings. Because of this, it is necessary to fill as many buckets as possible (>90% of all buckets), operate with the largest vertical emittance possible (i.e., equal emittances in both planes), and stretch the bunch length by factors of 3-4 with harmonic RF systems. Hard x-ray sources would have more flexibility in those choices. The combination of those mitigation methods is sufficient to reach the diffraction limit up to 2 keV in a 2 GeV ring of 200 m circumference.

Besides the aforementioned need for strong magnet gradients and, therefore, small magnet and vacuum apertures with the resulting needs for advanced vacuum systems, the performance optimization outlined above leads to the need for other advanced solutions. The very strong focusing required for low emittance introduces large chromatic aberrations in the lattice that must be corrected using strong sextupoles. The sextupole field non-linearities introduce resonance driving terms that reduce dynamic and momentum acceptance, potentially leading to low lifetime and even the inability to inject beam into the machine. While it is desirable to preserve the capability for off-axis injection if possible, beam can be injected into a small dynamic acceptance on-axis if necessary. With on-axis injection, electrons in the bucket are kicked out and replaced with the newly injected electrons (“swap-out” injection [6]). In the specific case of a low energy ring with round beams to mitigate IBS, injection using accumulation would usually be impossible.

The need to fill most buckets to mitigate IBS drives the need to use pulsers with small rise and fall times (<10 ns), but moderately long flat-tops (50 ns). While such magnets require some R&D, most parameters have been demonstrated as part of linear collider development.

Besides these technology challenges, swap-out injection actually has advantages over the more commonly used accumulation. These include potentially relaxed requirements on magnet errors in the storage ring, smaller injection losses, and the possibility to use undulators with small, round apertures that promise to provide ultimate performance for experiments requiring polarization control.

## Accelerator Lattice

Continuing with our case study, a DLSR upgrade of the ALS could be based on a multi-bend achromat lattice with nine bends (9BA) per sector, and would retain twelve arcs as in the existing ALS [7]. No damping wigglers are foreseen and round beams would be used. Magnet apertures would be reduced by roughly a factor of three down to a pole radius of 12 mm. Lattice optimization using driving term analysis and multi-objective genetic algorithms has been carried out, yielding a candidate lattice with the desired emittance with small beta functions and reasonable dynamic and momentum aperture. In addition to sextupoles, three families of octupoles would be used. The lattice functions, as well as the magnet arrangement are shown in Figure 1.

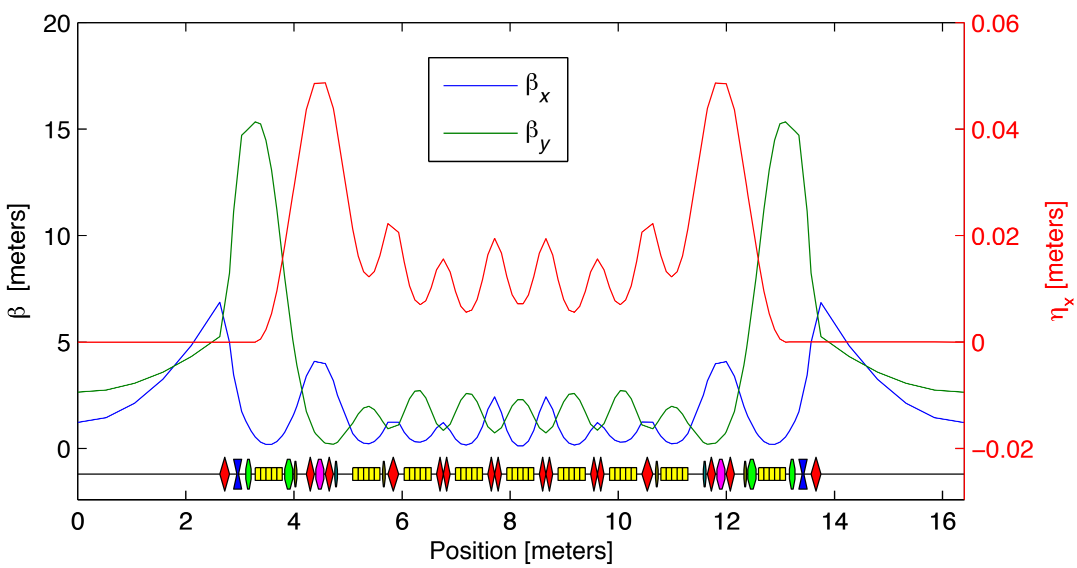


Figure 1: Candidate lattice for a hypothetical ALS upgrade using a nine bend achromat. Gradient dipoles are shown in yellow, quadrupoles in red and blue, sextupoles in green and magenta, and octupoles in brown and grey.

### *Lattice Performance*

We examined the use of on-axis injection with bunch train swap-out and an accumulator ring. The accumulator ring will act as a damping ring, where its lattice will allow for off-axis injection from the existing injector and the extracted low emittance beam is injected on-axis into the small dynamic aperture of the multi bend achromat ring. The dynamic and momentum apertures of the candidate lattice are sufficient (>100$\sigma_{x,y}$ and 2.5-3%, respectively) to allow high efficiency on-axis injection and provide good beam lifetime of several hours.

As already discussed, IBS can lead to an increase in the six-dimensional emittance of the particle bunch. This is especially true when the emittance is very small, the beam energy is moderate, and the bunch intensity is fairly high. IBS calculations were carried out using the high-energy approximation of the Bjorken-Mtingwa theory [8]. The mitigation of the impact of the IBS effect on the equilibrium emittance will be achieved by operating with round beams and stretching bunches by a factor of 3-4 with a 3rd harmonic RF system. Figure 2 shows the predicted steady state emittance including the effects of insertion devices, the harmonic cavities, and IBS. At 500 mA the emittance is about 50 pm-rad in both planes, consistent with the goal of reaching the diffraction limit up to about 2 keV.

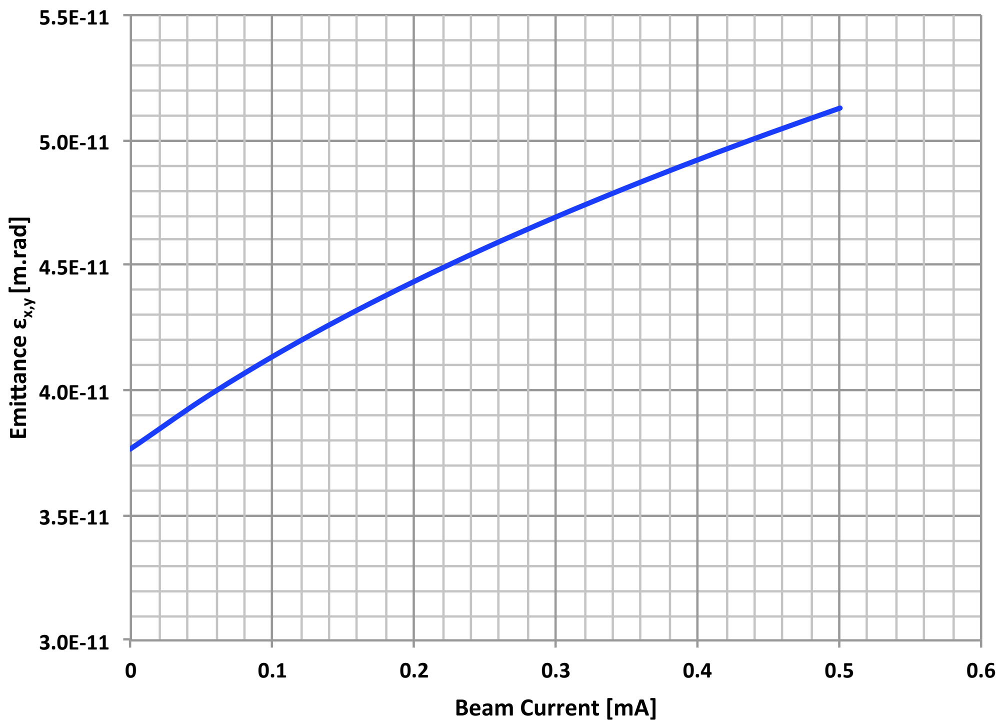


Figure 2: Predicted increase in emittance due to intrabeam scattering including the effects of a typical full set of insertion devices.

Another consequence of the small magnet and vacuum system apertures is the fact that both the resistive wall impedance and the geometric impedances of transitions become higher. The bunch lengthening cavities play an important role in mitigating this effect. Calculations show acceptable growth rate for resistive wall driven instabilities. Similarly, the harmonic RF system also helps to increase the threshold for the single-bunch, transverse mode coupling instability, raising it above the bunch charge necessary for 500 mA.

Including all effects, the predicted straight section beamsizes are around 10 μm in both planes, very similar to typical vertical beamsizes in 3rd-generation light sources. The electron beam ellipse is matched well to the diffraction ellipse leading to excellent brightness performance for soft x-rays. Figure 3 shows the resulting brightness envelope predicted for a hypothetical ALS upgrade assuming undulators with 4 mm physical aperture using superconducting technology, compared to the existing ALS.

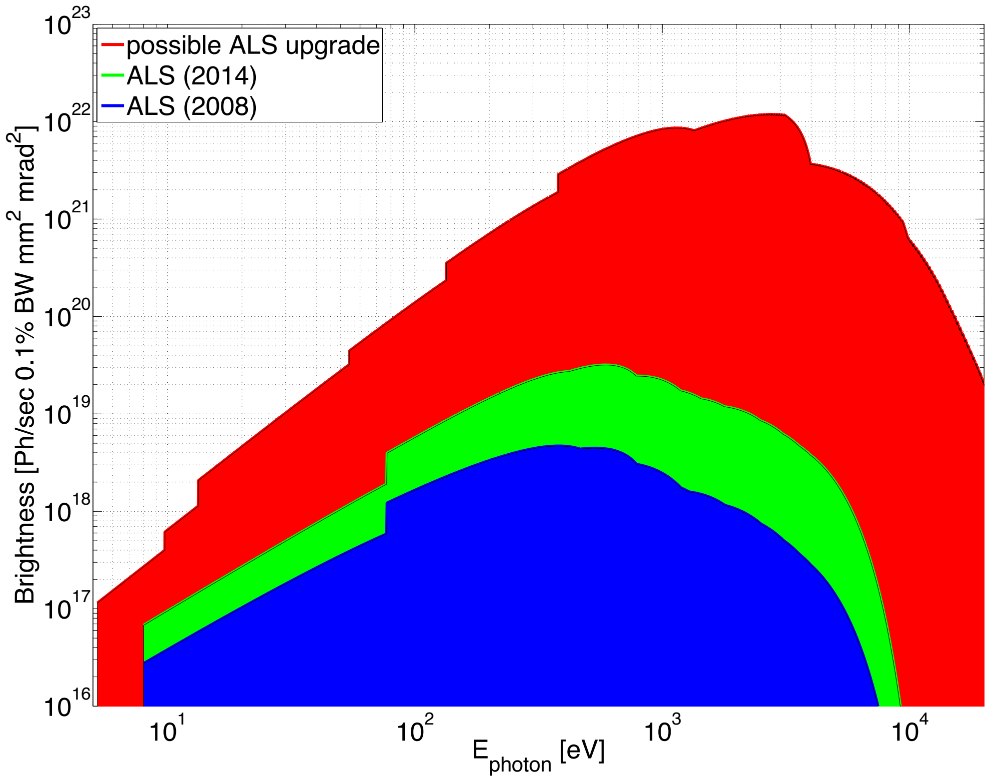


Figure 3: Brightness envelopes for a possible DLSR upgrade of the ALS (red) and the existing ALS (before and after the recent upgrades blue/green).

## Diffraction-Limited Storage Ring R&D

An R&D program funded by internal laboratory funds was started at LBNL to further develop the technologies necessary for diffraction-limited storage rings. It initially involves five areas, and focuses on the specific needs of soft x-ray facilities:

- Vacuum system/NEG coating of small chambers,
- Injection/pulsed magnets,
- RF systems/bunch lengthening,
- Magnets/radiation production with advanced radiation devices,
- Beam physics design optimization.

Some small-scale hardware prototypes have already been built (see Figure 4). The work will expand in the future to demonstrate necessary key technologies at the component and/or subsystem level and include new areas like photon beamline optics.

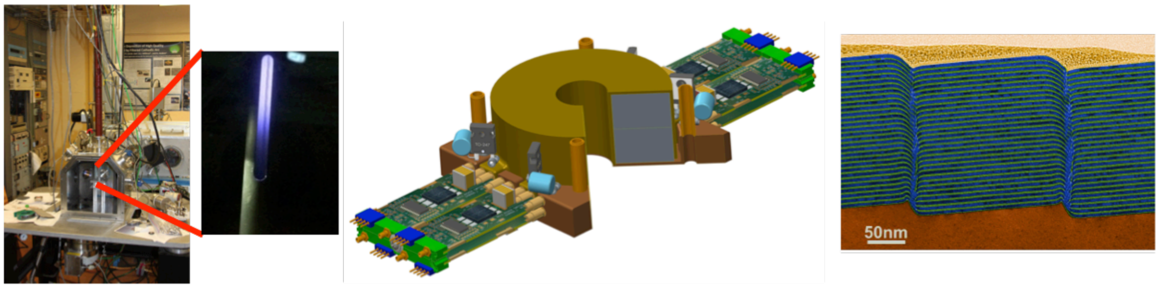


Figure 4: Examples of R&D work at LBNL geared towards diffraction-limited rings. Left: Very small aperture (<7mm) vacuum systems. Middle: Fast magnets for beam swap-out. Right: Brightness preserving photon optics.

## Summary

Improvements in brightness and coherent flux of about two orders of magnitude over operational storage ring based light sources are possible using multi bend achromat lattice designs. Such improvements can be implemented as upgrades of existing facilities, making use of the existing infrastructure, thereby reducing cost and time needed to reach full scientific productivity on a large number of beamlines. Some of the design choices for diffraction limited storage rings are impacted by the choice of spectral range for which the facility is designed. Specifically for soft x-rays it is possible to reach the diffraction limit in both planes with a ring of moderate size (200 m circumference) and beam energy (2 GeV) using round beams. Because of the strong energy scaling of intrabeam scattering, and photon beam heat load, as well as the energy scaling of achievable focal lengths for quadrupoles (and sextupoles), performance trade-off studies for such lower energy rings lead to some design choices different from facilities optimized for hard x-rays.

## References


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